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# Cr:LiCaAlF<sub>6</sub> Laser Pumped by Visible Laser Diodes

Richard Scheps

**Abstract**—A Cr:LiCaAlF<sub>6</sub> laser has been pumped for the first time using visible laser diodes. Two commercial 10 mW laser diodes were polarization combined to demonstrate lasing in a low loss resonator. In addition, a higher power 665 nm laser diode was used to pump the laser, producing 15.9 mW CW and 51.8 mW pulsed at 10 Hz. Optical characterization of the gain medium was performed using a dye laser. Gain, loss, slope efficiency, and the dependence of the threshold on pump wavelength are reported.

DIODE pumping of rare earth-doped solid state lasers has been actively developed over the past several years. However, for many applications requiring a specific single wavelength, or requiring wavelength agility, the fixed frequencies produced by these devices make wavelength matching difficult. In addition, the narrow absorption linewidths that are typical of many rare earth-doped lasers restrict the pump bandwidth to 1 or 2 nm. This requires one to compromise the high cost of a narrow linewidth diode array with the low pumping efficiency of a broad bandwidth array. In contrast to the rare earth lasers, the transition metal Cr<sup>3+</sup>-doped vibronic lasers are broadly tunable over a range in excess of 100 nm, while the pump absorption bands are quite broad, generally peaking in the 650 to 700 nm range. Laser diodes emitting in this wavelength region have recently become available, and it has therefore been feasible to demonstrate the capabilities of several diode pumped Cr-doped solid state lasers.

The first demonstration of diode pumping was reported for alexandrite [1]. Recently a new Cr-doped crystal, Cr:LiCaAlF<sub>6</sub> (Cr:LiCAF), was developed [2] and shown to perform as well as the more mature alexandrite laser. For diode pumping, however, the Cr:LiCAF laser has two important advantages. The first is that the variation of the absorption coefficient with pump polarization is substantially reduced in Cr:LiCAF, allowing polarization combination of pump diodes similar to the technique used [3] in end-pumping Nd:YAG. The other is that absorption in the 660–680 nm wavelength range is much higher than in alexandrite. These advantages, coupled with highly efficient [2] performance under Kr<sup>+</sup> laser pumping, constitute a compelling basis for demonstrating diode pumping of Cr:LiCAF. The results of the first

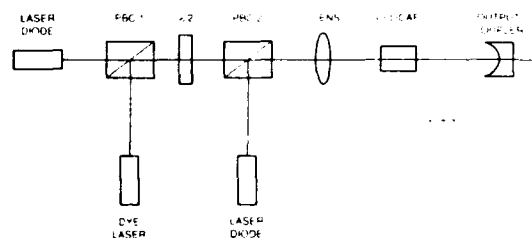


Fig. 1. Configuration of the pump and resonator optics. Two polarizing beam combiner cubes (PBC) are used to allow three optical sources to simultaneously pump the Cr:LiCAF crystal. The  $\lambda/2$  plate rotates the polarization of the two sources transmitted by PBC1, determining the fraction of each transmitted by PBC2.

diode-pumped operation of this material are reported below, along with optical characterization measurements including gain, loss, slope efficiency, and dependence of threshold power on pump wavelength.

The experimental arrangement is shown in Fig. 1. The Cr:LiCAF laser consists of a 7.75 mm long, 2 atomic % Cr<sup>3+</sup>-doped laser crystal and a 5 cm radius of curvature output mirror in a nearly hemispherical resonator. The exterior facet of the Cr:LiCAF crystal was coated for high reflectivity (HR) at the laser wavelength and the interior facet was antireflection (AR) coated. The pump geometry is a modified version of the standard [3] polarization combination configuration, in this case allowing three optical sources to simultaneously pump the rod. The  $\lambda/2$  plate serves as a variable pump beam attenuator. By rotating the polarization of the orthogonally polarized beams transmitted by the first polarization beam combiner cube (PBC1), the  $\lambda/2$  plate determines the fractional power of each that will be reflected by the second polarization beam combiner cube (PBC2). The power transmitted by PBC2 will pump the Cr:LiCAF crystal. With a polarization rotation of 0 or 90°, only the laser diode or dye laser power will be transmitted by PBC2, respectively. This pump configuration proved remarkably convenient since the dye laser could be used for initial alignment of the resonator, after which its power could be gradually "dialed out" of the pump axis while the laser diode power was simultaneously "dialed in." In addition, with the dye laser off, rotating the  $\lambda/2$  plate attenuated the laser diode pump power, facilitating threshold and slope efficiency measurements. In all cases it was found that the polarization of the pump beam did not affect the polarization of the laser output, which was always parallel to the crystallographic *c* axis. The pump light was focused onto the crystal with a 5 cm focal length lens.

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Data on the operation of the Cr:LiCAF laser were taken with three separate light sources: a pair of 10 mW 670 nm laser diodes, a higher power 265 mW laser diode, and a dye laser. The two 10 mW laser diodes operated at 672 and 673 nm, respectively. Due to the broad absorption of the Cr:LiCAF, temperature tuning of the diode wavelength was not necessary. This permitted using lasers that were commercially packaged and collimated, greatly facilitating alignment. The focussed spot diameter was measured to be no greater than 10  $\mu\text{m}$ , the resolution limit of the diagnostic apparatus. Both diodes were index guided, nominally single mode devices. However, spectral measurements showed two longitudinal modes operating simultaneously in each laser, due perhaps to optical feedback from the collimating lens. The dye laser was capable of operating between 610 and 680 nm, but when used as an alignment device was set to 670 nm. The higher power laser diode produced 106 mW CW and 265 mW (peak power) pulsed with no external cooling. The output linewidth was 0.21 nm, centered at 666.8 nm under full CW power. The diode architecture is that of a strained layer single quantum-well GRINSCH design, and will be described in more detail separately [4], [5].

With an HR output coupler the incident pump power from the two 10 mW laser diodes required to reach threshold was 14.8 mW. The maximum power from the two diodes incident upon the Cr:LiCAF crystal was 18.3 mW, which produced a laser output power of 540  $\mu\text{W}$ . Accounting for the transmission losses at the pump wavelength due to the imperfect dichroic coating on the exterior facet of the crystal (4.5%) and the transmission of the pump light through the crystal (12.0%), the slope efficiency based on absorbed power is 18%. The output amplitude gave no indication of temporal spiking, and the output spectrum, shown in Fig. 2, was highly stable, centered at 795 nm. The untuned emission is red-shifted from the Cr:LiCAF gain peak, but as had been previously discussed [6], the emission wavelength near threshold for a tunable laser is a function of the spectral dependence of the reflective coatings. A demonstration of repetitive Q-switched operation was performed using a mechanical chopper [6] at 3 kHz. Output pulses of 240 ns duration were measured with an average output power of 215  $\mu\text{W}$ .

Optical characterization measurements of the laser resonator were most readily performed with the dye laser. When using this laser in the configuration shown in Fig. 1 the  $\lambda/2$  plate was rotated so that most of the dye laser power was reflected by PBC2, allowing operation of the dye laser well above its threshold while delivering only threshold-level power to the Cr:LiCAF rod. This renders the dye laser less sensitive to optical feedback from reflections in the pump optics train, providing greater amplitude stability and hence more accurate results. The gain and loss of the resonator were determined by measuring the threshold power as a function of output coupling [7]. The round-trip resonator loss is  $6.1 \times 10^{-4}$  and the round-trip small-signal gain is  $8.6 \times 10^{-5} P_i$  ( $\text{mW}^{-1}$ ), where  $P_i$

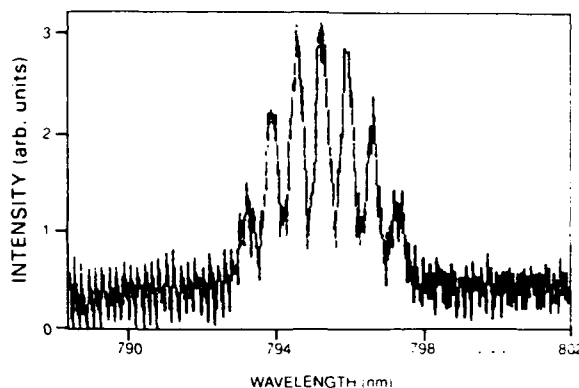


Fig. 2. Output spectrum of diode-pumped Cr:LiCAF taken with an optical multichannel analyzer (OMA). The central wavelength is 795.2 nm and the full width at half-maximum (FWHM) is 3 nm. Structural peaks are 0.7 nm apart and are the result of interference effects in one of the optical coatings. Spectrum shown represents the accumulation of 100 sequential traces across the OMA detector.

is the pump power. The gain is similar to that previously reported [6] for Cr:LiCAF using dye laser pumping. The absorbed pump power required to exceed threshold was measured as a function of wavelength and found to be constant ( $13.1 \pm 1.5$  mW) over the 610–680 nm wavelength range accessible to the dye laser. The slope efficiency as a function of output coupling was also measured. The lowest reflectivity output coupler available, a 98.7%  $R$  mirror, provided the best measured slope efficiency. This was 41% based on incident pump power, and 50% based on absorbed power.

In order to achieve higher diode-pumped output power, a GRINSCH laser diode more powerful than those commercially available was used. This diode replaced the dye laser in Fig. 1. Neither of the commercial diodes were operating during these measurements. The diode package was an open heat sink and its output was readily collimated with a high numerical aperture multielement lens corrected for 665 nm. The collimated output was focussed to a 10  $\mu\text{m}$  diameter spot on the face of the Cr:LiCAF crystal. To operate the uncoated diode at 106 mW CW per facet required approximately 560 mA. The diode was also operated at 10 Hz with 200  $\mu\text{s}$  long pulses. Because of the higher pump power available, the HR output coupler which had been used when pumping with the two 10 mW diodes was replaced with a 99.6% reflective mirror for CW pumping and a 99.3% reflective mirror for pulsed operation. The best output power obtained was 15.9 mW CW and 51.8 mW pulsed, corresponding to optical conversion efficiencies of 15% and 20%, respectively.

In summary, a Cr:LiCAF laser has been operated diode pumped using both commercially available 670 nm lasers and a higher power GRINSCH diode. In addition, characterization of the resonator including gain, loss, slope efficiency, and the dependence of the threshold power on pump wavelength have been measured. This is the first report of diode pumping of this material, and demonstrates that polarization combination of laser diodes to

pump Cr:LiCAF is practical. Because of its substantial tuning range and long spontaneous emission lifetime, diode-pumped Cr:LiCAF is ideally suited to applications which require efficient operation of a tunable solid-state laser. Applications involving frequency agility, such as secure optical communications, or requiring a specific narrow frequency, such as LIDAR, are two examples.

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